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ABSTRACT

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To be presented to the European Physical Society High Energy Physics Conference (Brussels, Belgium); a similar talk was given at the International School on Particles and Cosmology (Baksan, Russia), and this is an update of talks given at the XVth Moriond Workshop (Dark Matter in Cosmology, Clocks, and Tests of Fundamental Laws) and Beyonf the Standard Model (Lake Tahoe, CA).

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ABSTRACT

The LSND experiment has observed a beam-on minus beam-off excess of events which are consistent with oscillations of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. While the chance that this is a statistical fluctuation is $< 10^{-3}$, evidence for neutrino mass cannot be claimed unless the effect appears also in the $\nu_\mu \rightarrow \nu_e$ channel, currently being analyzed. If $\nu_\mu \rightarrow \nu_e$ is observed also, then $\Delta m^2_{\mu c}$ is most likely ~ 6 eV^2. Should a neutrino (ν_μ or ν_e) have a mass ~ 2.4 eV, then current models of a low density universe do not work, and a critical density universe is favored. If two nearly degenerate neutrinos exist ($\nu_e \rightarrow \nu_\tau$ to explain the solar neutrino deficit or $\nu_\mu \rightarrow \nu_\tau$ to account for the atmospheric ν_μ/ν_e ratio), then the resulting $\sim 20\%$ hot dark matter when combined with $\sim 75\%$ cold dark matter and $\sim 5\%$ baryonic matter explains the structure of the universe on all scales and solves the age problem, because the Hubble constant has to be close to 50 km$\cdot$ s$^{-1}\cdot$ Mpc^{-1}. The possible pattern of neutrino masses, described here, would then also serve as a guide to a more encompassing theory beyond the Standard Model of particle physics.

1. LSND Experiment

Neutrino mass is a central issue for particle physics, because neutrinos are massless in the Standard Model, and for cosmology, because the relic neutrinos, if massive, would have profound effects on the structure of the universe. Determining the pattern of neutrino masses could provide guidance to a more encompassing particle theory, and the existence of neutrino mass could solve many of the outstanding problems in astrophysics and cosmology. To discover neutrino masses in the range relevant to cosmology, the one tool available is the observation of neutrino oscillations.

The Liquid Scintillator Neutrino Detector (LSND) is designed to detect neutrinos originating in a LAMPF proton beam stop. The oscillation searches are carried out by focusing on energy ranges in which the produced ν's are overwhelmingly ν_μ as opposed to ν_e, or the produced $\bar{\nu}$'s are overwhelmingly $\bar{\nu}_\mu$ as opposed to $\bar{\nu}_e$. Then observation of ν_e's or $\bar{\nu}_e$'s, respectively, in excess of the number expected from conventional sources may be interpreted as evidence for neutrino oscillations. (A direct lepton number violating process is also a possibility.) A paper reporting evidence for such an excess in the channel $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ has been submitted to Physical Review Letters.[1] Analysis is underway on the more difficult $\nu_\mu \rightarrow \nu_e$ channel. Because the two measurements are done in different neutrino energy ranges and have

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different backgrounds and systematics, the eventual comparison of their results will provide not only independent evidence for oscillations, but also stronger constraints on possible neutrino mass differencess than either measurement alone.

Protons from the LAMPF 800-MeV linac produce pions in a 30-cm-long water target about 1 m upstream from the copper beam stop. For the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search, the $\bar{\nu}_\mu$'s are provided via $\pi^+ \rightarrow \mu^+\nu_\mu$, followed by $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ decay-at-rest. The relative $\bar{\nu}_e$ yield is $\sim 4 \times 10^{-4}$ for $E_\nu > 36$ MeV. LSND detects $\bar{\nu}_e$ by $\bar{\nu}_e p \rightarrow e^+ n$, followed by a γ from $np \rightarrow d\gamma$ (2.2 MeV). Requiring an e^+ energy above 36 MeV eliminates most of the accidental background from $\nu_e {}^{12}C \rightarrow e^- X$ (the detector not distinguishing between e^+ and e^-), while an upper energy requirement of 60 MeV allows for the $\bar{\nu}_\mu$ endpoint plus energy resolution. For the $\nu_\mu \rightarrow \nu_e$ search, the ν_μ's arise from $\pi^+ \rightarrow \mu^+\nu_\mu$ decay in flight, with 60 MeV $< E_\nu <$ 160 MeV, staying above the maximum energy of decay-at-rest ν_e's. LSND detects ν_e by $\nu_e {}^{12}C \rightarrow e^- X$.

The experiment is located about 30 m from the neutrino source and is shielded by the equivalent of 9 m of steel. The detector, an approximately cylindrical tank 8.3 m long by 5.7 m in diameter, is under ~ 2 kg/cm^2 of overburden to reduce the cosmic-ray flux and is inside a liquid scintillator veto shield. On the inside surface of the tank 1220 8-inch Hamamatsu phototubes provide 25% photocathode coverage with uniform spacing. The tank contains 167 metric tons of liquid scintillator consisting of mineral oil (CH_2) and 0.031 g/l of b-PBD. The low scintillator concentration allows the detection of both Čerenkov and scintillation light; this in turn provides a means of $e^\pm$ identification.

The behavior of the detector is calibrated using a very large sample of "Michel" $e^\pm$ from the decays of stopped cosmic ray muons. These $e^\pm$ are in just the right energy range for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search. The phototube time and pulse height signals are used to reconstruct the $e^\pm$ track with an average r.m.s. position resolution of ~ 30 cm, an angular resolution of $\sim 12^0$, and an energy resolution of $\sim 7\%$.

Even with all the shielding, there remains a very large background to the oscillation searches from cosmic rays. There are four lines of defense. First, an in-time veto rejects the muons; however, decay $e^\pm$ and neutrons remain a problem. Second, a veto is imposed on any event occurring too soon after even low-level activity in the detector or veto shield; a hardware cut of ≈ 7 muon lifetimes is extended in software to ≈ 18 muon lifetimes for the $\bar{\nu}_e$ search. Third, $e^\pm$ ID criteria, using the quality of the position fit along with angular and timing information, strongly suppress cosmic ray neutrons. Fourth, any remaining cosmic ray background is very well measured because about 12 times as much data are collected outside of the beam spills as inside.

LSND collected beam data for 1.5 months in 1993 and 3.5 months in 1994; the next run will begin in August, 1995. Data from the 1993 and 1994 runs have been analyzed to search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ neutrino oscillations.

The first step in searching for $\bar{\nu}_e$ interactions was to select e^+ candidates with particle ID information consistent with a $\beta \sim 1$ particle and passing the cosmic ray

rejection cuts just described. The reconstructed position of the track midpoint was required to be > 35 cm from the locus of the phototube faces. The overall e^+ selection efficiency is $28 \pm 2\%$. In $36 < E_e < 60$ MeV, there are 135 such events with the beam on and 1140 with the beam off, giving a beam-on excess of 46.1 ± 11.9 events. (This still includes beam-related backgrounds.)

The second step is to require a correlated 2.2 MeV γ with a reconstructed distance, Δr, within 2.5 m of the e^+, a relative time, Δt, of less than 1 ms, and a number of hit phototubes, N_γ, between 21 and 50. The efficiency for neutron detection with these cuts is 63%. To determine if such a γ is correlated with the e^+ or from an accidental coincidence, a function R of Δr, Δt, and N_γ is defined to be the ratio of approximate likelihoods for the two hypotheses.

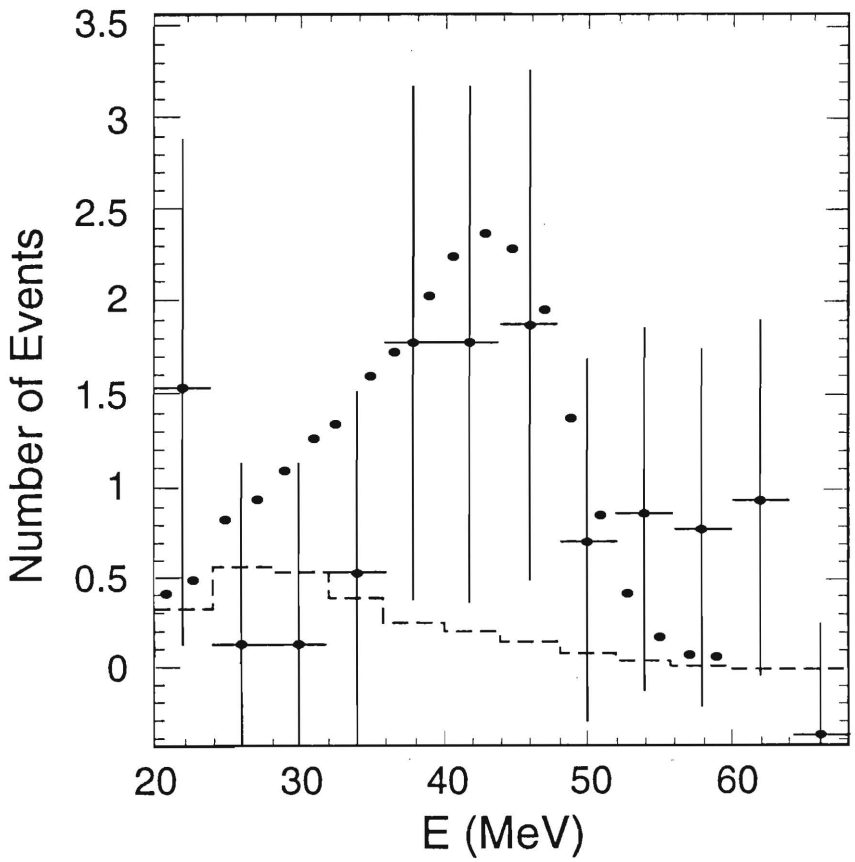

Figure 1. The e^+ energy distribution, beam-on minus beam-off, for events with an associated 2.2 MeV γ with $R > 30$. The e^+ efficiency drops for $E < 28$ MeV. The dashed histogram shows the expected background from known neutrino interactions. The dotted curve is the expected distribution for neutrino oscillations in the limit of large Δm^2, normalized to the excess between 36 and 60 MeV.

To determine whether there is a significant $\bar{\nu}_e$ excess, a cut was made at $R > 30$. This cut has an efficiency of 23% for events with a recoil neutron and

an accidental rate of 0.6% for events with no recoil neutron. Figure 1 shows the beam-on minus beam-off energy distribution for $R > 30$. There are 9 beam-on and 17 beam-off events between 36 and 60 MeV, corresponding to a beam-on excess of 7.7 events. Of these, 0.79 ± 0.12 are estimated to be beam-related background, implying a net excess of 6.9 events. The probability that this excess is a statistical fluctuation is $< 10^{-3}$.

The size of the excess is, however, better determined by utilizing all e^+ data between 36 and 60 MeV. The total numbers of beam-on and beam-off e^+ events with correlated γ's were obtained from a likelihood fit to the R distributions at the e^+ positions. The result, after subtracting the neutrino background with a neutron, is $16.4^{+9.8}_{-8.9}$ events. If this is interpreted as due to neutrino oscillations, the oscillation probability is $(0.34^{+0.20}_{-0.18} \pm 0.07)\%$, where the second error is systematic.

Cosmic-ray background is most intense in the outer regions of the detector and where the veto has gaps – beneath the detector and near the lower corner of the upstream end. However, Kolmogorov tests did not show significant problems with the distribution of the excess events. If an additional cut were made to omit the $\approx$ 50% of the detector with highest cosmic ray backgrounds, one could no longer demonstrate an $R > 30$ excess (2 events with an expected background of 0.7), but this result and the fit oscillation probability of $(0.10^{+0.18}_{-0.13} \pm 0.02)\%$ are not statistically inconsistent with the full-acceptance result.

The two-generation neutrino oscillation probability is

$$P = (\sin^2 2\theta) \sin^2(1.27 \Delta m^2 L/E),$$

where E is the neutrino energy (MeV), L is its flight distance (m) before interaction, and Δm^2 is the mass-squared difference (eV^2). The 90% C.L. upper and lower limits of P, found using the R distributions of all e^+ data between 36 and 60 MeV, were converted using this equation into 90% C.L. limits of $\sin^2 2\theta$ as functions of Δm^2. Figure 2 shows these results, along with limits from KARMEN,[2] E776 at BNL,[3] and the Bugey reactor experiment.[4]

LSND does not claim this result as proof of neutrino oscillations, and backgrounds will continue to be studied. However, it is clear that something potentially extremely interesting has been observed. To elucidate further just what is going on, the two most important additional needs are to test the oscillation hypothesis in the $\nu_\mu \rightarrow \nu_e$ channel and to collect more statistics from future LSND running.

The $\nu_\mu \rightarrow \nu_e$ channel is crucial to knowing if neutrino oscillations are being observed because the potential systematic problems are quite different from the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ case. If oscillations are confirmed, the $\nu_\mu \rightarrow \nu_e$ data should determine Δm^2. Figure 2 shows possible oscillation antinodes at 2, 6, and 10 eV^2, whereas the higher energy of $\nu_\mu \rightarrow \nu_e$ would put the first two antinodes at 6 and 18 eV^2. The only compatible value of Δm^2 would then be 6 eV^2 to have a sufficiently small

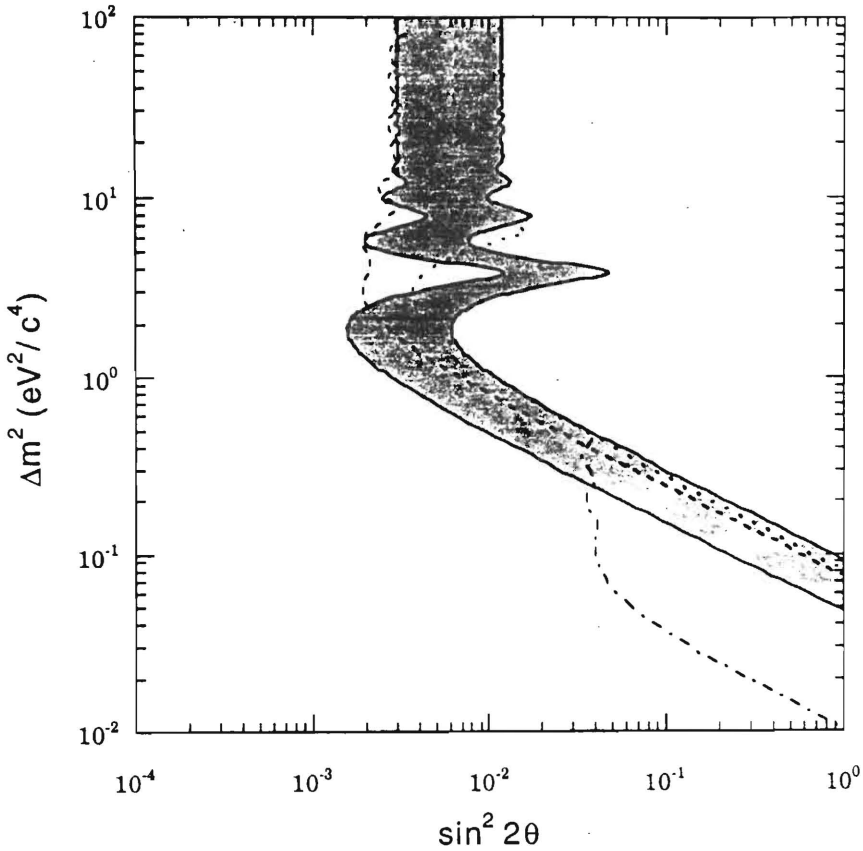

Figure 2. Results from interpreting the excess signal from all e^+ data as due to two-generation neutrino oscillations. The two edges of the shaded band are the 90% C.L. limits of $\sin^2 2\theta$ as a function of Δm^2. Not included is the 20% systematic uncertainty in the LSND normalization. Also shown are 90% C.L. limits from Ref. 2 (dotted histogram), Ref. 3 (dashed histogram), and Ref. 4 (dot-dashed histogram).

mixing angle. Such a value implies that either the ν_e or ν_μ is $\sim$ 2.4 eV.

2. Cosmological Consequences of a Positive LSND Result.

Should a 2.4 eV neutrino exist, it would contribute $\sim$ 10% to the dark matter of the universe for critical density ($\Omega = 1$). This is a contribution to Ω equivalent to as much baryonic matter as nucleosynthesis permits and is more than an order of magnitude more than the baryonic matter observed so far. Models of the universe which utilize a density lower than critical (typically $\Omega \leq 0.3$) would then not have enough cold dark matter to produce sufficiently early structure formation, since the 2.4 eV neutrinos (hot dark matter) would wash out density fluctuations.[5] The only other models which come close to fitting the observed structure of the universe on all scales have $\Omega = 1$, so such a neutrino likely forces critical density, the only time-stable value for no cosmological constant.

One species of 2.4 eV neutrino would not provide a cold plus hot dark matter model which would fit structure information well. These models were created because the cold dark matter model (CDM), which was a fair approximation to the structure of the universe, when normalized to the COBE data produced too much structure on small scales, since baryons readily clump around the cold dark matter. The first cold + hot dark matter models (CHDM) had $\sim$ 30% neutrinos and fit structure on all scales very well[6] because the free streaming of the neutrinos reduced density fluctuations on small scales. Unfortunately, this damping of density perturbations also caused structure to form too late. Reducing the neutrino content to $\sim$ 20% allowed early enough structure formation,[7] as measured by the observed density of cold hydrogen and helium gas at large red-shift (z = 3.0–3.5), which was determined by the absorption of distant light in damped Lyman α systems. With all the mass in one neutrino species, this otherwise successful model (CνDM) overproduced clusters of galaxies. In other words, the CνDM model worked well at all distance scales except $\sim 10h^{-1}$Mpc, where h is the Hubble constant in units of 100 km$\cdot$s$^{-1}\cdot$Mpc^{-1}. If $h = 0.5$ and $\Omega = 1$, the mass of the neutrino required in the CνDM model is $94h^2\Omega F_\nu = 4.7$ eV, for a neutrino fraction of Ω, $F_\nu = 0.20$. If instead this mass is divided between two nearly degenerate neutrino species, the motivation for which will be discussed shortly, then this Cν^2DM model turned out to have a remarkable property.[5] While 4.7 eV in one neutrino species or two makes essentially no difference at very large or very small scales, at $\sim 10h^{-1}$Mpc the larger free-streaming length of the 2.4 eV neutrinos tends to wash out fluctuations and lowers the abundance of clusters. Thus the model (Cν^2DM) with two, 2.4 eV neutrinos fits structure information on all scales.

This point is illustrated in Fig. 3, where the CDM, CHDM (which has one 7 eV neutrino), CνDM, and Cν^2DM models are compared along with two other models which are modifications of the original CDM model. One is a "biased" CDM model in which the normalization is varied to get an overall improvement in fit. The other is a low-density model (ΛCDM) which adds a cosmological constant, Λ, to keep the time independence of the density by making $\Lambda + \Omega = 1$. In the figure all models except biased CDM are normalized to COBE, and five other comparisons are made to data at various distance scales in terms of very generous errors in those observations. Expressing those errors as "standard deviations" should not be taken too literally in some cases. The lines have no significance, except to aid the eye in connecting the 6 points for each type of observation.

The Cν^2DM model works only if $\Omega = 1$ and $h = 0.5$. Although there are determinations of h near that value with very small stated errors, there are also values around 0.7 to 0.8, also with errors given which are very small, but such values produce difficulties with $\Omega = 1$. Should the Cν^2DM model be proved correct by terrestrial determinations of neutrino mass, the long-sought answers concerning h and Ω would be settled. That terrestrial experiments can settle the issues results from the fact that there are $\sim 10^2/\text{cm}^3$ of each species of the three active neutrinos (ν_e, ν_μ, ν_τ) everywhere. Unfortunately, direct detection of these relic neutrinos, whatever their mass may be, appears to be impossible at this time, since they are

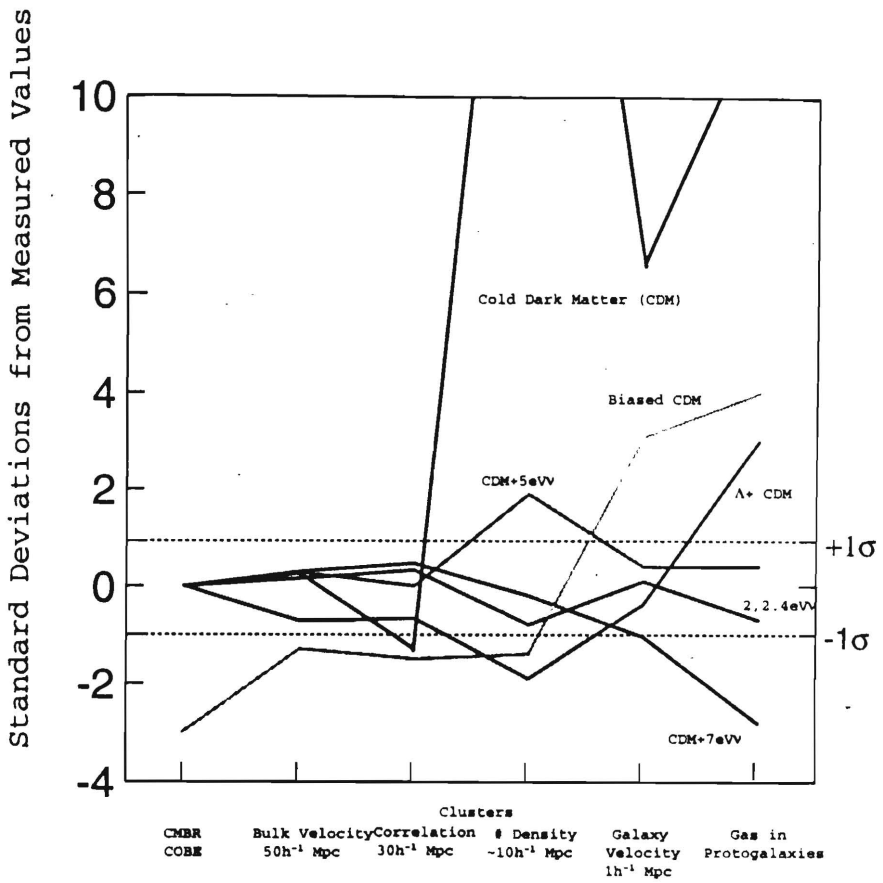

Figure 3. Various cosmological models compared with observations over a wide range of distance scales. That fitting the data best has cold plus hot dark matter, with the latter supplied by two species of 2.4 eV neutrinos.

now near the temperature of the cosmic microwave background radiation and hence have too little energy.

3. Possible Neutrino Mass Patterns

The reason the large-scale simulations for the Cν^2DM model were tried was a scenario[8] for neutrino masses designed to account for three hints of neutrino mass, one of which is the need for some hot dark matter. Of the other two, one is the deficit of ν_es from the sun observed by four experiments of three types. Of those three types, two have to be making incorrect observations in order for an astrophysical explanation of the deficit to work.[9] A solution in terms of neutrino oscillations requires that the mass-squared difference between the ν_e and whatever it turns into be no more than $\Delta m^2_{ei} \sim 10^{-5}$ eV^2. The second indication for neutrino mass results from evidence for a deficit of ν_μs relative to ν_es in atmospheric secondary cosmic rays. There are compatible results from three experiments[10] and new information from Kamiokande.[11] The latter includes accelerator confirmation of the ability to

separate ν_e and ν_μ events, as well as an independent higher energy data set giving not only a ν_μ/ν_e ratio agreeing with the lower energy data, but also a zenith-angle (hence source-to-detector) dependence compatible with oscillations requiring $\Delta m^2_{\mu i} \sim 10^{-2}$ eV^2. The explanation of the observations in terms of the oscillation $\nu_\mu \to \nu_e$ is almost excluded by data from the Bugey[4] and Krasnoyarsk reactor oscillation experiments. Also, in the higher energy Kamiokande data,[11] the muons display the zenith-angle dependence, whereas the electrons do not, as would be expected if the ν_μ were affected by oscillations, but the ν_e were not. Finally, the calculated ν_e and ν_μ fluxes—backed by measurements of μ fluxes—agree with the ν_e data but show a ν_μ deficit.[12] Thus $\nu_\mu \to \nu_\tau$ oscillations are favored as an explanation of this atmospheric ν_μ deficit.

If the solar ν_e and atmospheric ν_μ deficits and the need for some hot dark matter arise from the existence of neutrino mass, then there are only two viable patterns of those masses[8] for a hierarchical mass structure. If there are no sterile neutrinos, the only possibility allowed by the small Δm^2 values required by $\nu_e \to \nu_\mu$ for the solar deficit and $\nu_\mu \to \nu_\tau$ for the atmospheric one is $m_{\nu_e} \approx m_{\nu_\mu} \approx m_{\nu_\tau} \approx 1.6$ eV to give the needed ~ 4.7 eV for hot dark matter.[8] If neutrinos are Majorana particles, for which there is strong theoretical prejudice, then neutrinoless double beta decay experiments are close to excluding this alternative, unless there is three-neutrino maximal mixing, which requires a vacuum oscillation solution to the solar ν_e deficit.[13]

A sterile neutrino may be introduced, provided it does not exceed the limit[14] of 3.1 neutrino species at the time of nucleosynthesis. This limitation can be avoided only for the favored small mixing angle solution for solar $\nu_e \to \nu_s$, since any other use of a light ν_s would bring it into equilibrium in the early universe. The ν_μ and ν_τ then provide the atmospheric ν_μ deficit and share the dark matter, making $m_{\nu_\mu} \approx m_{\nu_\tau} \approx 2.4$ eV. A combination of the SNO and SuperKamiokande experiments will be able to demonstrate $\nu_e \to \nu_s$ to check this mass pattern, which is consistent with the possible LSND oscillation result.

There is a possible conflict with the $\bar{\nu}_\mu \to \bar{\nu}_e$ interpretation of the LSND data from supernovae. It is believed that much of heavy element production occurs in the outer neutrino-heated ejecta of Type II supernovae, where rapid interactions with the large number of neutrons can take place, the so-called r process. A limitation on the mixing of ν_μ and ν_e comes about because energetic ($\langle E \rangle \simeq 25$ MeV) ν_μ or ν_τ could convert via an MSW transition to ν_e inside the region where the r process is believed to occur. Such converted ν_e would have a much higher energy than the thermal ν_e ($\langle E \rangle = 11$ MeV), because the latter have charged current interactions with electrons. Since the cross section for $\nu_e + n \to e^- + p$ rises rapidly with energy, the energetic ν_e would deplete the neutrons, stopping the r process. Calculations[15] of this effect limit $\sin^2 2\theta$ for $\nu_\mu \to \nu_e$ to $\lesssim 10^{-4}$ for $\Delta m^2_{\mu e} \gtrsim 2$ eV^2, apparently in conflict with the LSND results.

Whether the four-neutrino mass scheme[8] just described is ruled out is unclear at this time, because the possible effects of a sterile neutrino on the supernova

dynamics has not yet been explored sufficiently. Another alternative is to avoid the bound by inverting the mass order and making the ν_e heavier than the ν_μ.[16,17,18] This possibility would seem to run into a problem with the observations of IMB and Kamiokande of a $\bar{\nu}_e$ signal from supernova 1987A, because the MSW resonance condition would then occur for $\bar{\nu}_\mu \to \bar{\nu}_e$, and these detectors were especially sensitive to higher energy $\bar{\nu}_e$. Calculations[16] indicate that this effect is not as strong as one would have expected, however.

Three neutrino mass schemes become possible with this mass inversion. Esthetically the most pleasing is one in which $m_{\nu_\mu} \ll m_{\nu_e} \approx m_{\nu_\tau} \approx 2.4$ eV, with $\Delta m^2_{e\tau} \approx 10^{-5}$ eV^2 for the larger angle MSW solution to the solar ν_e deficit, and the hot dark matter shared by ν_e and ν_τ. If the ν_e is a Dirac particle, either of the two MSW solutions could be used, but the global L_e–L_τ symmetry (where the L's are Lepton numbers) needed to suppress neutrinoless double beta decay requires near maximal mixing for a Majorana ν_e. A gauge theory for this arrangement of neutrino masses has been worked out[18] using a conventional $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model with the see-saw mechanism supplemented by a global $U(1)_{L_e - L_\tau}$ symmetry. If this is a correct scheme, the atmospheric ν_μ deficit must have an explanation other than being a manifestation of neutrino mass.

To explain also the atmospheric ν_μ/ν_e ratio by neutrino oscillations, variations of the two schemes given above are needed in which there is a ν_e–ν_μ mass inversion. With this inversion, $m_{\nu_e} \approx m_{\nu_\mu} \approx m_{\nu_\tau} \approx 1.6$ eV would work[17] for a Dirac ν_e, or for a Majorana ν_e only if there is a maximal mixing angle scenario (as in Ref. 13), and which requires the vacuum oscillation solution of the solar ν_e problem.[18] The other alternative[16] requires $m_{\nu_e} \approx m_{\nu_s} \approx 2.7$ eV (for the solar ν_e deficit) and $m_{\nu_\mu} \approx m_{\nu_\tau} \approx 1.1$ eV (for the atmospheric ν_μ deficiency). The ν_s does not contribute to hot dark matter for the small-angle MSW solution, since its mixing with the ν_e is insufficient to bring it into equilibrium in the early universe (avoiding the nucleosynthesis bound), so the ν_μ and ν_τ need to make up the rest of the ~ 5 eV. In this case the ν_e must be Dirac, and it is not clear how well such a model fits the universe structure, as is also true for the other scheme of three nearly equal mass neutrinos. Detailed simulations have not yet been done.

4. Conclusions

The LSND beam-on minus beam-off excess of events of the type $\bar{\nu}_e + p \to e^+ + n$, $n + p \to d + \gamma$ (2.2 MeV) is statistically significant evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. Barring the existence of some as yet undetected spurious source of these events, this requires that the ν_μ and/or the ν_e have mass, providing the first laboratory violation of the Standard Model of particle physics. Essential to making this result certain would be confirming evidence from the data obtained simultaneously on $\nu_\mu \to \nu_e$, since the energies involved, detection reaction, backgrounds, and systematic uncertainties are all different from the $\bar{\nu}_\mu \to \bar{\nu}_e$ case.

If this result is correct, it can be combined with other constraints and hints

of neutrino mass to deduce acceptable patterns of those masses which could provide guidance to a more encompassing theory. One possibility is that $\nu_e \to \nu_s$ for the solar ν_e deficit, $\nu_\mu \to \nu_\tau$ to explain the ν_μ/ν_e ratio from atmospheric neutrinos, and ν_μ and ν_τ share the role of the hot dark matter which would constitute 20% of the mass of the universe. The most likely Δm^2 provided (but far from proved) by the LSND results is consistent with the needed ν_μ mass of ~ 2.4 eV, if the ν_e mass is much smaller. While the sterile neutrino, ν_s, may make possible avoiding the bound on ν_e–ν_μ mixing coming from the r process in supernovae, a sure way to avoid this is to make the ν_e heavier than the ν_μ. A scheme having $m_{\nu_\mu} \ll m_{\nu_e} \approx m_{\nu_\tau} \approx 2.4$ eV provides the hot dark matter and $\nu_e \to \nu_\tau$ for the solar problem, but requires an explanation for the atmospheric ν_μ deficit which does not relate to neutrino mass. Including this last issue again forces the introduction of ν_s but now with other unsatisfactory features.

If even one species of neutrino (ν_e or ν_μ) has ~ 2.4 eV mass, as indicated by the LSND result, then Ref. 5 shows that low-Ω cosmological models do not work, since structure forms much too late. This result then settles the ultimate fate of the universe, expansion slowing toward zero but never recollapse. If there are two neutrinos of about this mass (ν_μ and ν_τ or ν_e and ν_τ) then not only is $\Omega = 1$, but also $h \approx 0.5$, and the issue of the expansion rate or age of the universe is also settled.[5] The effect of the lightest kind of elementary particle which can have mass may be remarkably great.

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